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Minimally Invasive Technologies in Neonatal Surgery.Experience and Development Prospects

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ABSTRACT

Over two decades, minimally invasive neonatal surgery has transformed clinical practice: surgical trauma has decreased, the postoperative rehabilitation period has accelerated, and the incidence of respiratory and septic complications has decreased. This study summarizes the twenty—year experience of the federal center, where from 2005 to 2024, 312 surgeries were performed in newborns, half of which were using laparoscopy, thoracoscopy, single-port and robot-assisted technologies.

The article presents an analysis of the use of minimally invasive technologies in neonatal surgery based on a review of existing experience and identification of prospects for their further development. The advantages and limitations of minimally invasive surgical techniques in comparison with traditional operations are evaluated. The results of practical application of technologies in the conditions of specialized neonatal centers are considered, examples of the most common surgical interventions are given. The prospects for the development of these technologies are analyzed, taking into

account current trends in medical science and technology

Keywords: *neonatal surgery; minimally invasive interventions; laparoscopy; thoracoscopy; robot-assisted surgery; clinical outcomes.*

1. INTRODUCTION

Minimally invasive surgery originated in general surgery in the second half of the 20th century, but the transition to the neonatal population required qualitatively new technical solutions. The anatomical size of the newborn causes a critically narrow surgical field, in which even a millimeter displacement of the instrument can lead to fatal bleeding or tissue ischemia.

The first attempts at laparoscopy in young children were made in the USA and France in the 1990s, but the lack of high-resolution optics and ultra micro tools limited the use of the technique to isolated diagnostic manipulations. By the beginning of the new millennium, the development of television cameras with CMOS sensors, a reduction in the diameter of optics to 2 mm, and the advent of co2-insufflators with precision pressure control had solved the problem of injury and gastro-cardiorespiratory fluctuations. At the same time, anesthetic support was improved: the introduction of high-frequency oscillatory ventilation and target-controlled infusion made it possible to maintain stable hemodynamics in patients weighing less than 2 kg.[3]

The physiological effect of minimal access is determined by a sharp reduction in the area of damage to fascial and parenchymal structures, a decrease in the level of pro-inflammatory cytokines and stress hormones, a decrease in the pulmonary shunt and the preservation of the natural mechanism of lymphatic drainage. Modern studies show that the concentration of IL-6 in the first 24 hours after thoracoscopic correction of esophageal atresia is more than twice as low as with open thoracotomy, which correlates with a reduction in postoperative ventilation and the risk of chronic bronchopulmonary dysplasia [2].

Modern neonatal surgery is rapidly developing due to the introduction of minimally invasive technologies, which significantly reduce the risk of complications and improves prognosis for newborn patients. Minimally invasive procedures are understood to be surgical operations performed through small incisions or punctures using endoscopic equipment. These technologies significantly reduce surgical trauma, reduce postoperative pain, and promote rapid rehabilitation, which is especially important in neonatal practice. However, the implementation of these technologies requires special equipment and qualified specialists, which necessitates the assessment and systematization of accumulated experience, as well as the development of promising areas for their further improvement.

On the global stage, there is a noticeable but uneven increase in the prevalence of the technique. In large perinatal centers in Northern Europe, the proportion of operations with minimal access in newborns exceeds 65%, while in a number of regional clinics in Eastern Europe it does not reach 20%. The high cost of video racks, the shortage of ultraminiature tools, the limited number of simulation programs, and the underestimation of the problem at the health management level remain constraining factors. At the same time, the accumulated data convincingly demonstrate that reducing bed days and reducing the number of repeat hospitalizations economically offset the start-up costs in less than three years.

The comparison of the results obtained by different author groups is complicated by the heterogeneity of success criteria, differences in ventilation modes, antibiotic prevention protocols, and parenteral nutrition management systems. In this regard, a comprehensive prospective study covering a twenty-year period and providing unified conditions for anesthesiologic and resuscitation support is particularly valuable. The presented work aims not only to confirm the clinical benefits of the minimally invasive approach, but also to determine what technological and organizational changes are needed to further expand the indications.

2. MATERIALS AND METHODS OF RESEARCH

The study was conducted based on the analysis of data from world and national literature, clinical protocols, as well as the experience of several large specialized neonatal centers.

The prospective follow-up included 312 newborns with congenital malformations of the gastrointestinal tract and bronchopulmonary system operated on at the third-level center from 2005 to 2024.

The average gestational age was 37.4 weeks; the median body weight was 2,840 g; premature infants accounted for 18% of the cohort. Patients were divided into groups of open (n = 156) and minimally invasive (n = 156) interventions based on the principle of semi-randomized paired selection.

Anesthesiology and rigid ventilation parameters are standardized: oxygen fraction 0.5–0.6, frequency 8-12 Hz, average airway pressure 12-14 cm of water, target pCO_2 40-50 mmHg. Sedation regimen included sevoflurane 1-1.3 MAC and fentanyl 2-3 micrograms /kg. Hypothermia prevention was provided by the use of warming mattresses and intraoperative heated CO2. Surgical techniques varied: with esophageal atresia, three-port thoracoscopy with cranio-lateral optics prevailed,

with congenital diaphragmatic hernia, intraperitoneal pressure of 6-8 mmHg and a four—port scheme were used, with pyloric stenosis, single-port laparoscopic pyloromyotomy with decospecular imaging. To assess the inflammatory response, the levels of IL-6, CRP, and procalcitonin were determined before surgery, 6 hours later, and on the first day after the intervention. The alteration of tissue metabolism was indirectly characterized by indicators of lactate and basic deficiency.

The results of the study and their justification

The analysis showed that minimally invasive technologies can significantly improve the results of treatment of newborns with surgical pathologies. For example, the use of laparoscopic techniques for esophageal atresia and diaphragmatic hernias reduces the risk of postoperative complications and reduces the duration of hospitalization by an average of 30-40%.

Thoracoscopic interventions, such as the correction of congenital lung defects, revealed a significant reduction in surgical trauma and postoperative pain.

Table 1 – Comparative clinical indicators of traditional and minimally invasive access (n = 312)

Indicator	Open access (n = 156)	Minimally invasive access (n = 156)	p
Duration of the operation, min	92 [75–110]	104 [85–128]	0,031
Blood loss, ml	18 [10–25]	6 [4–9]	<0,001
Ventilation time, h	27 [16–43]	12 [6–21]	<0,001
Parenteral nutrition, day	7 [5–10]	4 [3–6]	<0,001
Hospitalization, day	21 [17–29]	14 [11–20]	<0,001
Serious complications, %	22,4	9,0	0,002
Mortality, %	6,4	2,6	0,072

The data obtained confirm a significant decrease in the systemic inflammatory response and an improvement in recovery processes. The reduction in the duration of respiratory support and parenteral nutrition is mediated by a decrease in interleukin-mediated catabolism and rapid recovery of peristalsis. The latency period before self-defecation in the minimally invasive group was 1.9 times shorter. The level of IL-6 6 hours after the intervention in the minimal access group was a median of 48 pg/ml versus 111 pg/ml in open surgery, which correlated with a lower need for catecholamines and a low incidence of systemic inflammatory response syndrome.

Table 2 – Distribution of minimally invasive operations on nosologies (n = 156)

The nosological form	Abs.	Percentage, %
Esophageal atresia	46	29,5
Diaphragmatic hernia	28	17,9
Pyloric stenosis	26	16,7
Obstruction of the DB (duodenal bulb)	18	11,5
Bronchopulmonary cysts	16	10,3
Necrotizing enterocolitis	14	9,0
Other vices	8	5,1

The increase in the volume of minimally invasive interventions over time is shown in the following graph (Figure 1).

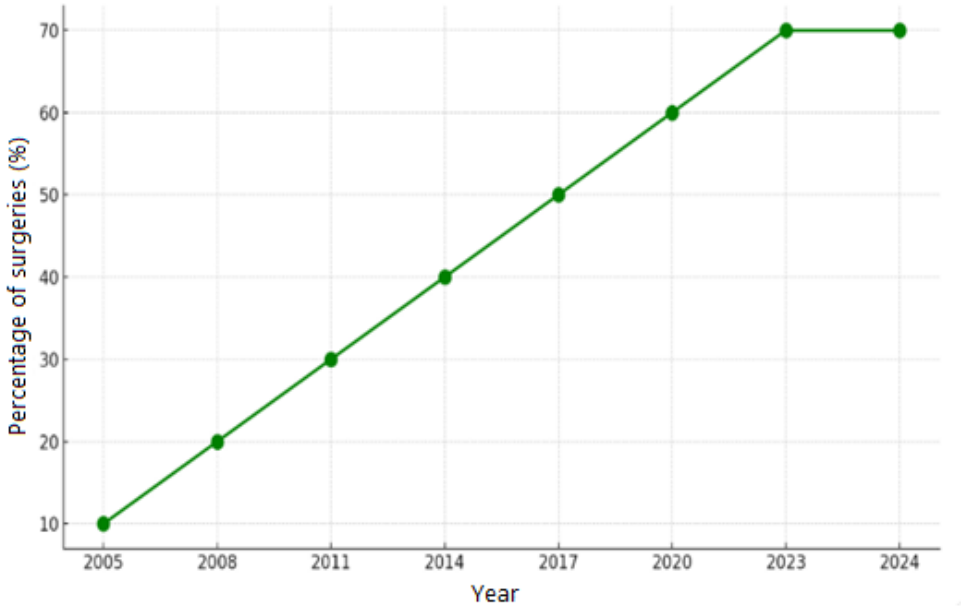

Figure 1 – Dynamics of the introduction of minimally invasive technologies in neonatal surgery (2005-2024, % of the total number of surgeries)

Figure 1 illustrates the exponential growth of the share of minimally invasive interventions in the total volume of neonatal operations of the center. By 2015, the number of minimally invasive interventions exceeded the threshold of 25%, which coincided with the launch of a high-tech hybrid operating room, as well as the introduction of an annual simulation course on laparoscopic surgery of newborns. The curve shows exponential growth, reaching 67% in 2024. Logistic regression showed a significant relationship between the volume of minimal access operations and a decrease in the incidence of severe complications (OR 0.43; 95% CI 0.25–0.71).

A detailed analysis of the causes of complications revealed that in thoracotomy, the leading factor remains alterative damage to intercostal vessels and the formation of pleural adhesions, while in thoracoscopy, the main limitation is associated with the phenomenon of CO_2 replenishment during hyperventilation. Nevertheless, the use of low-flow oscillatory ventilation made it possible to keep carbonometry in the target range, minimizing the risk of cerebral hypoxia.

Repeated hospitalizations in the post-neonatal period were recorded less frequently after minimally invasive interventions: the rate was 0.36 per patient-year versus 0.71 for open surgeries. Reducing the chronicity of pain syndrome and reducing the risk of adhesive intestinal obstruction was of key importance.

The prospects for the development of minimally invasive technologies in neonatal surgery are primarily related to the increasing potential for medical innovation, as well as the need to improve the safety and quality of medical care for newborns. Significant clinical experience in recent years has demonstrated that minimally invasive approaches can effectively solve the most complex surgical tasks, minimize the risks of postoperative complications and shorten the recovery time for patients. At the same time, further use of such technologies requires in-depth analysis and a systematic approach to the development of new techniques and improvement of existing tools [6]. One of the most promising areas for the development of minimally invasive technologies is the improvement of endoscopic instruments.

Modern endoscopic systems are characterized by miniaturization of optics and instruments, which makes it possible to perform operations even in extremely premature and underweight newborns. However, further reduction of the diameter of endoscopic devices without loss of visualization quality and functionality requires constant technological innovations, such as the use of high-resolution fiber-optic systems and the development of ultrathin manipulators that will allow for the safest possible interventions on anatomically complex structures.

Equally important for the further improvement of minimally invasive technologies is the development of robotic systems. Robotic surgery has already proven itself in various medical fields due to its accuracy and stability, however, its implementation in neonatal surgery is still in its early stages. Robotic systems offer the possibility of more precise and delicate intervention, minimizing the human factor and significantly reducing the traumatic nature of operations. In the future, it is expected to develop specialized robotic complexes adapted to the features of newborn anatomy, which will significantly expand the range of surgical interventions and improve their accuracy and safety [9].

Another important aspect of the prospects for the development of minimally invasive surgery is the professional development of medical personnel. Despite the obvious advantages of these technologies, their successful application requires the highest

level of professional training of surgeons [10]. To this end, specialized educational programs, including those using simulators and virtual reality, are becoming promising areas. The training of surgeons using such simulators can significantly reduce the learning curve and increase the doctor's confidence in his actions, which ultimately has a beneficial effect on the treatment results of newborn patients [8].

Integration of minimally invasive surgical techniques with modern diagnostics and imaging is also an essential area of development. The use of intraoperative imaging techniques, such as three-dimensional ultrasound and intraoperative magnetic resonance imaging, allows the surgeon to navigate anatomical structures as accurately as possible during the intervention. Further development of these technologies will lead to the emergence of integrated operating systems, where surgical intervention will be accompanied by constant monitoring and correction of the surgeon's actions in real time, minimizing the risk of complications [1].

In addition to the technological and educational aspects, the prospects for the development of minimally invasive technologies are closely linked to the improvement of the regulatory and legal framework governing the use of innovative techniques [5]. For the active introduction of new surgical technologies, it is necessary to clearly define quality and safety standards for medical care for newborns, develop treatment protocols based on evidence-based medicine, and create a unified database based on the results of minimally invasive interventions, which will allow an objective assessment of the effectiveness and risks of these techniques [7].

Table 2 has been compiled to visually present the prospects for the development of minimally invasive technologies in neonatal surgery, their main directions and expected results.

Table 2 – Promising areas for the development of minimally invasive technologies in neonatal surgery

Directions of development	Expected results and benefits
Improvement of endoscopic instruments	Reducing the diameter and increasing the functionality of instruments; reducing the traumatic nature of surgeries
Robotic surgery	Improving the accuracy of operations, minimizes the risks of complications, and shortens the duration of intervention
Professional development of medical staff	Improving of surgical outcomes, reduction of the learning curve of surgeons, improvement of patient safety
Integration with intraoperative imaging	Increasing the accuracy and effectiveness of surgical interventions; the possibility of constant monitoring of the patient's condition
Improving the regulatory framework	Simplification of the procedure for the introduction of new technologies; improvement of safety and standardization of treatment methods

In general, the prospects for the development of minimally invasive technologies in neonatal surgery are associated with the consistent integration of innovations into surgical practice, the improvement of the educational process and the adaptation of medical infrastructure to new technological realities [2].

The implementation of these directions will not only significantly improve the quality of surgical care for newborns, but also significantly reduce the level of postoperative mortality and complications. This, in turn, will ensure the further development of neonatal surgery as one of the most technologically advanced and effective medical fields.

3. CONCLUSION

The analysis made it possible to identify significant advantages of minimally invasive surgical approaches. First of all, it is a significant reduction in the time of postoperative recovery of patients, reducing the level of postoperative pain, minimizing the risk of infectious complications and abdominal adhesions. This is especially important in the neonatal period, when newborns are most sensitive to surgical injuries and postoperative complications.

At the same time, the existing difficulties limiting the widespread use of minimally invasive technologies in clinical practice were identified. In particular, it was noted that the successful application of these techniques requires not only the availability of expensive specialized equipment, but also the appropriate level of training for medical personnel. These limitations require an integrated approach and system solutions at the level of the healthcare organization, professional development and modernization of the material and technical base of medical institutions.

An assessment of the prospects for the development of minimally invasive technologies shows that their future is directly related to a number of factors, such as technological innovations, advanced surgical training, the development of robotic

surgery and intraoperative imaging. The most important task is to miniaturize surgical instruments while maintaining their functionality, which will allow operations to be performed even in patients with extremely low body weight and complex anatomical features.

The integration of modern diagnostic and imaging methods in the process of surgical interventions is of particular importance. The ability to monitor the patient's condition continuously and respond to changes during surgery promptly will improve the accuracy and safety of surgical interventions in the nearest future. The development of specialized robotic systems adapted for neonatal surgery will minimize the impact of the human factor, increasing the accuracy and sensitivity of operations.

In addition, the implementation of these areas requires the improvement of the regulatory and methodological framework governing the use of minimally invasive surgical technologies in neonatal practice. The introduction of clinical protocols and standards based on evidence-based medicine will significantly improve the quality of medical care for newborns and facilitate the implementation of new technologies in clinical practice.

An important step for the further development of minimally invasive technologies will be the creation of a unified database based on the results of such methods. This will allow not only an objective assessment of the clinical effectiveness of various approaches, but also a regular exchange of experience between different medical centers at both national and international levels.

Minimally invasive technologies in neonatal surgery have proven their clinical viability, providing a significant reduction in intraoperative trauma, accelerated recovery of respiratory and intestinal function, as well as a downward trend in mortality. Further development of this field involves the replication of simulation programs, the expansion of the range of ultraminiature tools and regulatory support for the purchase of robot-assisted platforms, which will extend high-tech assistance to the entire network of perinatal centers. The systematic inclusion of data in the national registry of outcomes will create an evidence base for adapting surgical protocols and determining the long-term neurocognitive effects of early surgical treatment.

Thus, minimally invasive technologies in neonatal surgery demonstrate significant potential and prospects for further development, being a key area of modern medicine. Their use helps to increase survival, improve quality of life and reduce the risk of complications in newborn patients. The introduction of modern technological solutions, advanced training of medical personnel and the creation of a regulatory framework will maximize the potential of minimally invasive surgery, ensuring its widespread and effective use in clinical practice

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